

# Development of an anti-Compton veto for HPGe detectors operated in liquid argon using Silicon Photo-Multipliers

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## Abstract

A proof of concept detector is presented for scintillation light detection in liquid argon using Silicon Photo-Multipliers. The aim of the work is to build an anti-Compton veto for germanium detectors operated directly in liquid argon like in the GERDA experiment. Properties of the Multi-Pixel Photon Counter (MPPC) are studied at cryogenic temperatures. To increase the light collection efficiency of the MPPCs wavelength shifting fibers were used. A veto efficiency comparable to a similar setup with a Photo-Multiplier Tube was achieved.

*Keywords:* silicon photo-multiplier, anti-Compton veto, liquid Argon, germanium detectors

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## 1. Introduction

One of the biggest challenges in dark matter and double beta decay experiments is to achieve a background level that is smaller than the expected signal. A reduction of the background can be achieved by adding shielding to the experiment and by careful selection of the components. After the limit imposed by the radioactivity of the cleanest materials available will be reached further reduction is possible only with an active veto system.

The GERDA [1] experiment currently being commissioned is built for the search for neutrinoless double beta decay ( $0\nu2\beta$ ) with high purity germanium detectors (HPGe). The HPGe detectors are submerged directly in liquid argon (LAr). The LAr simultaneously acts as passive shielding and cryogenic cooling liquid.

The main source of background for the  $0\nu2\beta$  decay is the radioactivity of the surrounding material.  $\gamma$  photons hitting the HPGe detector undergo Compton scattering and very often deposit only part of their energy before escaping the detector. The half life limit on  $0\nu2\beta$  decay at the end will be determined mainly by the number of this kind of events.

The escaping  $\gamma$ s with high probability will deposit their energy in the nearby environment. If the nearby space is filled with scintillating material the escaping  $\gamma$ s can be detected and the events with partial energy deposition in the HPGe detector can be vetoed. Such an arrangement is called an anti-Compton veto because it strongly suppresses the Compton background between the  $\gamma$  lines.

In GERDA the liquid argon was chosen primarily because of its higher density compared to liquid nitrogen. In addition to that LAr like all noble liquids has the advantage of being an excellent scintillator. Ar scintillates in the VUV range emitting light at 128 nm. The properties of the scintillation light are well understood and described in the literature (see for example [2]). The scintillator properties of LAr offer the possibility to use the scintillation light as an anti-Compton veto for the HPGe detectors, a possibility which is unexploited so far in the current design of GERDA.

Earlier it was shown that with a LAr anti-Compton veto more than an order of magnitude suppression of the background can be achieved [3] around the Q value of the  $0\nu2\beta$  decay. Such a huge improvement could be decisive for the success of GERDA if it could be realized without increasing the radioactive background or changing the original design too much.

The main goal of this work is to provide a light detection solution for low background liquid scintillator experiments in general that is compatible with the stringent radiopurity requirements of dark matter and double beta decay experiments.

## 2. Anti-Compton veto with Silicon Photo-Multipliers

Traditionally an anti-Compton veto is built using Photo-Multiplier Tubes (PMTs). The PMTs have some important disadvantages. They are not well suited for a cryogenic environment and they contain components such as glass which have significant radioactive impurities. Furthermore the use of high voltage in an argon atmosphere is always a source of problems.

A novel photon detection device, the multipixel avalanche photodiode commonly called Silicon Photo-Multiplier (SiPM) could be an alternative to

PMTs in certain cases. SiPMs do not require high voltage and they have a quantum efficiency at least as high as PMTs. Their small mass is the guarantee that their contribution to the radioactive background will be low.

The SiPM is an array of Avalanche Photodiodes (APDs) operated in Geiger mode. It promises single photon resolution and good photon detection efficiency. For a detailed description and possible applications see for example [4].

A major disadvantage of existing SiPMs is their small active area. We will try to overcome this disadvantage by connecting wavelength shifting fibers (WLS) to it. The WLS fiber increases the effective surface and guides the trapped photons to the SiPM. Such a design would have the advantage of being compatible with the string design of GERDA.

To test the principle a small scale experiment was built up to measure the properties of SiPMs in a cryogenic environment and to demonstrate a reasonably high light collection efficiency in LAr.

In our experiments we used the Multi-Pixel Photon Counter (MPPC) made by Hamamatsu with  $1\text{mm}^2$  active surface. We chose the versions in ceramic case S10362-11-025C / -050C / -100C with 1600, 400 and 100 pixels respectively.

### *2.1. Properties of SiPMs in a cryogenic environment*

MPPCs were already characterized at liquid nitrogen (LN) temperatures in [5] and [6]. The main goal of our studies was to determine the breakdown voltage dependence on the temperature for the specimens we used. We also describe in this section the electronic setup that was used during the experiment.

One property of the MPPCs that one immediately notices is that the pulse shapes change at low temperatures. The pulses become longer and their amplitude smaller (Fig.1). The waveforms can be explained by the internal structure of the MPPC. The temperature dependent quenching resistor changes its value by an order of magnitude between room temperature and LN. The decay time of the pulse is given by the pixel capacity times the resistance of the quenching resistor. For a detailed study see [7].

The long pulses with smaller amplitudes made it difficult to record good resolution spectra especially when the device was operated in a noisy environment with long cables from the detector to the front end electronics. In order to recover the single photon resolution and to measure the gain independently of the temperature we read out the MPPCs with charge sensitive

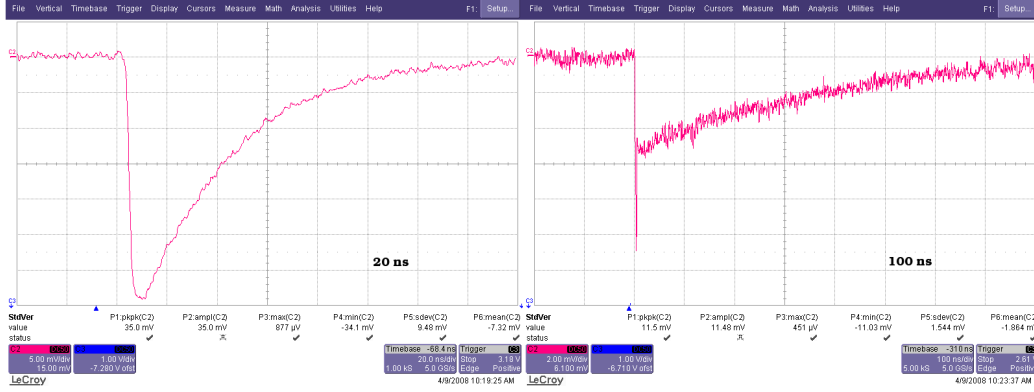


Figure 1: Difference in pulse shape at room temperature and in liquid nitrogen. The waveforms were recorded with a 100 pixel MPPC.

amplifiers. It was found that the CREMAT CR-111 and the CR-112 [8] have the optimal sensitivity. The integrated pulses were recorded with an XIA Pixie-4 DAQ [9]. The DAQ was optimized for germanium detectors but because we used charge sensitive amplifiers it could be used for the SiPMs with almost the same settings. In Fig.2 the pulse height spectrum of a 400 pixel MPPC is shown, operated in liquid nitrogen. The MPPC was separated from the preamplifier by a 50 cm long cable.

To measure the dark rate at different temperatures we wrapped the MPPCs in several layers of black tape and suspended them inside a dewar filled with liquid nitrogen. In the same experiment we measured three specimens with 100, 400 and 1600 pixels. A Pt-100 temperature sensor was also attached to the SiPMs. As the liquid nitrogen slowly evaporated we recorded dark pulses with the DAQ. At temperatures below 150 K the data acquisition was running for several hours until the first p.e. peak could be seen.

During one measurement the temperature was stable within a few degrees. For each temperature we recorded data at several bias voltages. From the amplitude of the single p.e. peak we could estimate the gain. From the bias voltage dependence of the gain we obtained the break-down voltage for each temperature.

Since in the final experiment we used only the 400 pixel MPPC here we show only the plots recorded with this device. The plots for the 100 and 1600 pixel devices look very similar. Fig.4 shows gain measurements at different temperatures and bias voltages.

After the temperature dependence of the breakdown voltage was known

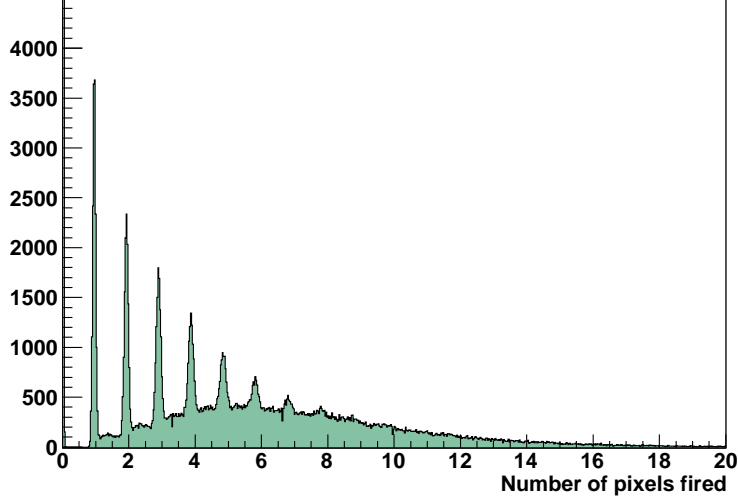


Figure 2: 'Photo-electron' spectrum recorded with a SiPM: the SiPM is separated from the preamplifier by a cable and is submerged in LN. Many p.e. peaks can be distinguished.

(Fig.5) we remeasured the dark rate as a function of temperature always at the same over-voltage. The results are shown in Fig.6. The measured dark rate at liquid nitrogen temperature is at the level of  $10^{-2}$  Hz at an over-voltage of 2.5 V for the 400 pixel device. For the MPPCs with 100 and 1600 pixels the dark rate at liquid nitrogen temperature is within the same order of magnitude as for the 400 pixel MPPC. The rates we measured are significantly smaller than what is reported in [5] but agree better with [6].

It is interesting to note that the dark rate drops below one Hz already at about 160 K close to the boiling point of Xe which makes this device especially interesting for low countrate cryogenic experiments.

## 2.2. Experimental setup

In order to increase the light collection efficiency we connected wavelength shifting fibers (WLS) to the SiPMs. The optical connection was realized with home made couplers. The coupler was made such that we could fine tune the position of the SiPM relative to the fiber. Each coupling was tuned by hand to the maximum light intensity seen by the SiPM.

The 128 nm light emitted by LAr cannot be absorbed by a WLS fiber or any plastic lightguide since such a short wavelength would be absorbed

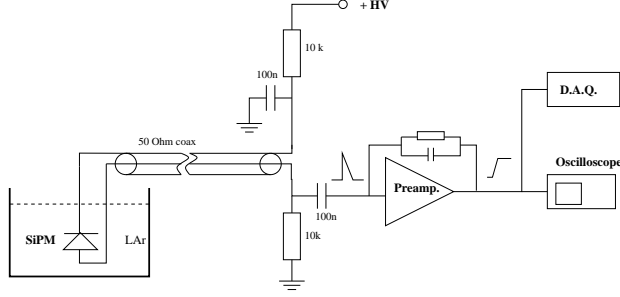


Figure 3: Electronic schematics of the setup

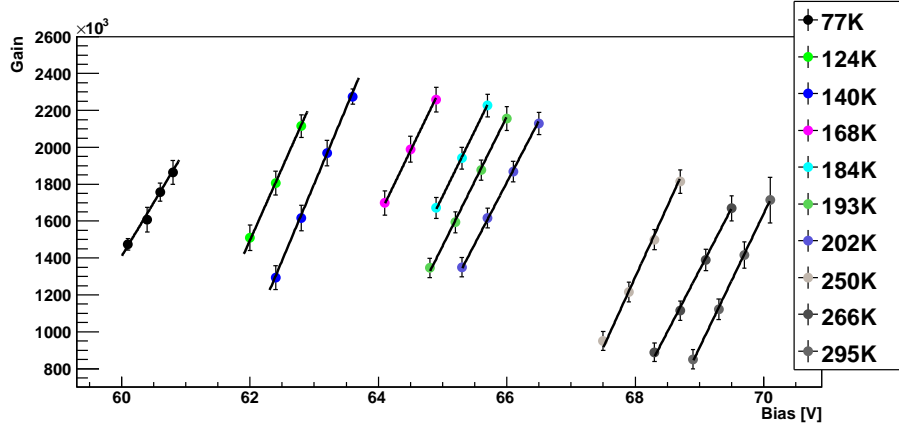


Figure 4: Gain as a function of bias voltage at different temperatures measured with the 400 pixel MPPC.

already in the cladding of the fiber before reaching the scintillating core.

We therefore coated a reflector foil (VM2000) with TPB (tetra-phenyl-butadiene) to serve as a primary wavelength shifter. The LAr volume delimited by the mirror foil creates an optical cavity where the only absorber is the WLS fiber. This arrangement increases substantially the amount of light collected in the fiber.

The emission spectrum of the TPB [10] and the absorption spectrum of most WLS fibers partially overlap. We chose the BCF-91A made by Saint-Gobain [11] which has a wide absorption peak. We estimated the conversion efficiency from 128 nm to 500 nm to be around 50%.

The choice of the WLS fiber was also motivated by the typical size of available fibers. The 1 mm  $\times$  1 mm square fiber is a reasonable match for

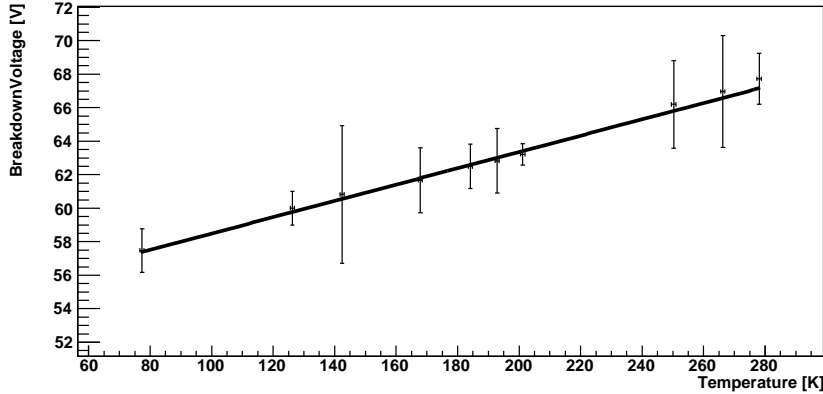


Figure 5: Break-down voltage as a function of temperature of the MPPC with 400 pixels

the  $1\text{mm}^2$  active area of the SiPM.

The major limiting factor in such a setup is the low trapping efficiency of the WLS fibers. The fibers with the highest trapping efficiency are the multicladd fibers with square cross section. The fiber used in the experiment was the BCF-91A,  $1\text{ mm} \times 1\text{ mm}$  square cross section, multicladd fiber with a trapping efficiency of 7.3% and an attenuation length of  $<3.5\text{ m}$  [11].

To hold the fibers inside the dewar a simple aluminium structure was designed. Three vertical bars with holes in them keep the coil of WLS fiber in place about 1 cm distance from the wall of the dewar. The distance between two parallel fibers is 1 cm. The holder with the fibers is shown on Fig.7. The volume enclosed by the fiber coil is approximatively 17 l. The VM2000 foil coated with a TPB solution was glued to the internal walls of our dewar.

The dewar was gas tight and it was kept under small overpressure. To remove the air it was flushed with Ar gas for about an hour before the filling with LAr started.

### 2.3. Light yield estimation

Attempts to use WLS fibers in combination with liquid scintillators were already made before. The description of a similar setup to ours can be found in [12].

To predict the light yield we have to make some reasonable assumptions and use estimates when measurements are not available. One important

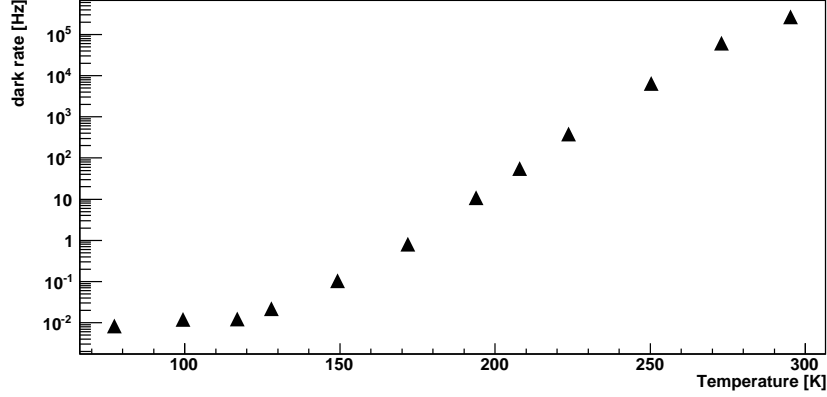


Figure 6: Dark rate of the 400 pixel MPPC as a function of temperature at 2.5 V over-voltage. The error bars from the statistical error are smaller than the symbols.

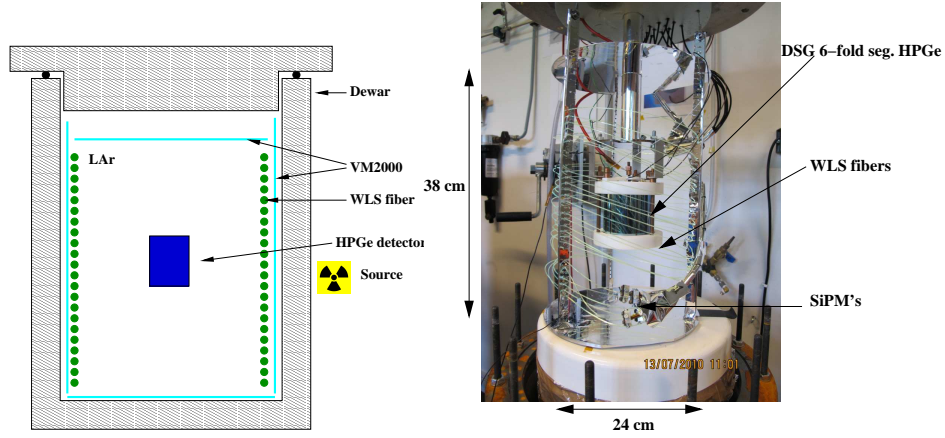


Figure 7: Conceptual drawing and the practical realization of the setup. An Al frame holds six 2.5m WLS fibers and 12 SiPMs inside the home made couplers. In the middle is the HPGe detector which was inserted only for the last experiment. Before the experiment the whole structure is lowered in the dewar below. The dewar has its wall covered with TPB coated VM2000 foil.

assumption we make is that the light inside our LAr volume is distributed uniformly across the fibers. In this case the light collected at the end of the fiber will be:

$$I = I_0 \frac{1}{L} \int_0^L e^{-\frac{x}{\lambda}} dx = I_0 \frac{\lambda}{L} (1 - e^{-\frac{L}{\lambda}}) \quad (1)$$



where  $I_0$  is the light intensity absorbed in the fiber,  $\lambda$  is the attenuation length and  $L$  is the length of the fiber.

Another important property of the setup is that the fibers are inside an optical cavity and the light that is not absorbed in the fiber will be reflected back and forth many times. The intensity that is finally absorbed in the fiber will be proportional to  $\frac{S}{1-(1-S)R}$ , where  $S$  is the ratio of the fiber surface to the reflector surface and  $R=0.95$  is the reflectivity of the VM2000 foil taken from [13].

Following [12] the photo electron yield can be calculated with the formula;

$$N = Y E_F E_{tr} I \frac{S}{1 - (1 - S)R} \times PDE \quad (2)$$

Where  $Y = 40000$  number of primary photons per MeV deposited energy,  $E_{tr} = 0.073$  is the trapping efficiency of the square multiclad fiber [11],  $PDE$  = Photon Detection Efficiency of the SiPM, taken to be 0.25 at 500 nm (see [14]),  $E_F$  = fluor efficiency, the probability that a 128 nm photon is converted to 500 nm. We assume that  $E_F$  is limited only by the absorption spectrum of the fiber (0.5 assumed).

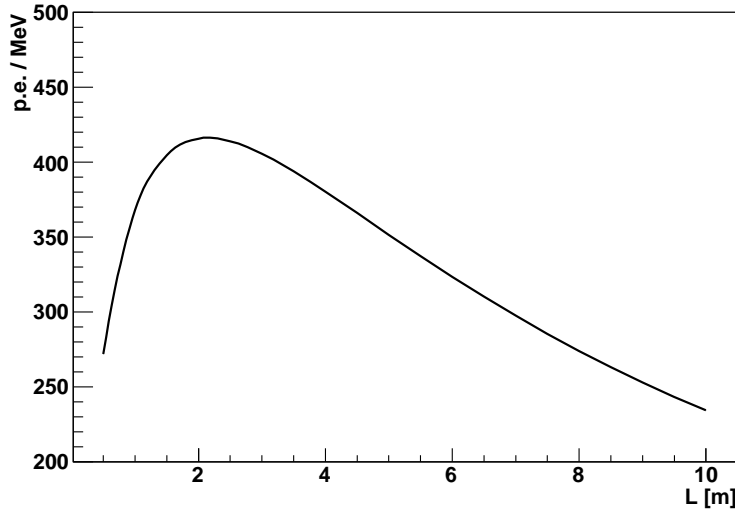


Figure 8: Estimated light yield as a function of fiber length for a six 1mm×1mm fiber setup in a 17 l volume optical cavity.

The formula was evaluated for the geometry of our setup. The light yield

will depend on the number of fibers used for the same total length. Because of the limitations imposed by the number of feedthroughs and electronic channels we used six fibers with a SiPM on each end. If we plot the estimated light yield as a function of fiber length (Fig.8) one can see that there is a clear maximum between 2 and 3 meters. For this reason we chose to use 2.5 m long fibers.

#### *2.4. Measured light yield*

Once the dewar was filled with liquid argon the setup was illuminated with  $^{60}\text{Co}$  and  $^{228}\text{Th}$  sources.  $^{60}\text{Co}$  emits two  $\gamma$ s in coincidence at 1173.2 keV and 1332.5 keV.  $^{228}\text{Th}$  has a strong line at 2.6 MeV. In the recorded spectra we expect to see an enhancement corresponding to about 1.2 MeV and another to 2.6 MeV respectively.

In contrast to the setup in [3] the sources were outside the dewar. An event was recorded by the DAQ when at least two SiPMs gave a signal above a 1 p.e. threshold. For each event we recorded 6  $\mu\text{s}$  long pulse shapes. Since we used charge sensitive preamplifiers the number of pixels hit was estimated off-line as the amplitude of the integrated pulse 6  $\mu\text{s}$  after the trigger. All 12 channels were calibrated separately and a sum spectrum of total number of SiPM pixels fired was created.

Because more than one photon can hit the same pixel simultaneously the SiPM is an inherently nonlinear device. The deviation from the linear response is negligible when the number of p.e.'s is small compared to the number of pixels. In our case in average about 30 pixels fired per channel for a typical event and we used a 400 pixel SiPM. Furthermore the hits are distributed within a time window of 6  $\mu\text{s}$  which is much longer than the recovery time of the device (about 200 ns). For simplicity we assume that the SiPMs operated always in the linear range and correction factors were not applied.

The spectra recorded with  $^{60}\text{Co}$  and  $^{228}\text{Th}$  sources show clear differences (Fig.9). The energy resolution for a 100 p.e./MeV collected is not expected to be better than 10%. In addition to that the peaks corresponding to fully absorbed  $\gamma$ s are smeared due to many factors:

- attenuation in the WLS fiber: the light yield is different if the light is absorbed close to the middle or close to the end of the fiber
- afterpulses and pixel to pixel cross-talk within one SiPM: the number of p.e.'s is smeared out by these two random processes.

- the 12 SiPMs each has a slightly different light collection efficiency. For cross calibration of the SiPMs we would need distinct features in the spectra of individual channels which were not seen.

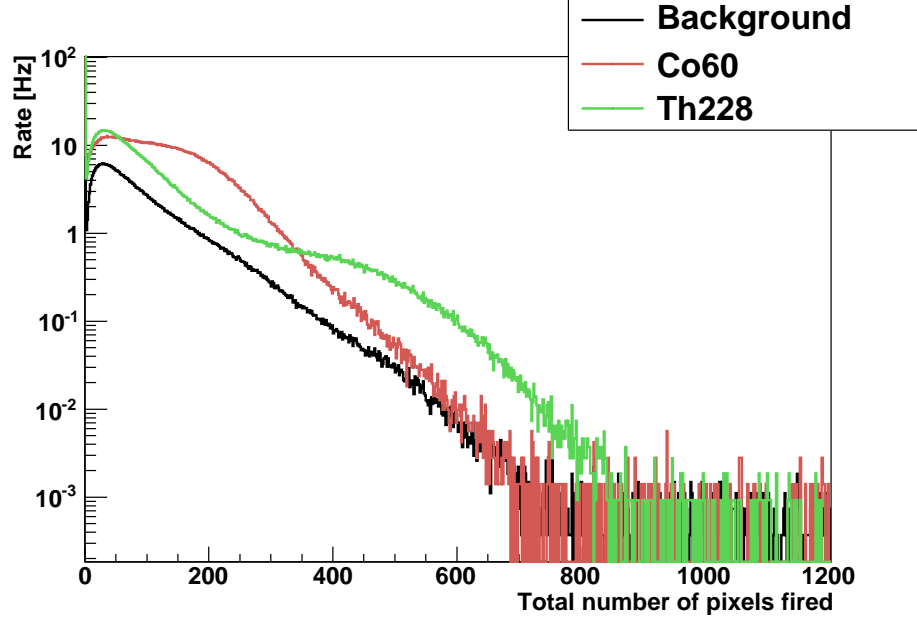


Figure 9: Response of the detector to the  $^{60}\text{Co}$  and  $^{228}\text{Th}$  sources

From the differences in the spectra recorded with the  $^{60}\text{Co}$  and  $^{228}\text{Th}$  sources we estimated a light yield between 100 and 200 p.e. for one MeV deposited energy. That is about 2 - 4 times lower than our estimate of about 400 p.e. calculated with Eq.2.

The reduced light yield can be largely explained with the quenching of the scintillation light by impurities in the Argon. It is well known that trace elements in ppm concentration can dramatically reduce the light yield. The Argon used was not the highest purity (Westfalen 4.6) and using a glass dewar we could not evacuate our setup before filling with LAr.

The Ar scintillation light has two components: a short component coming from the singlet excited molecular state  $^1\Sigma_u^+$  with 6ns decay time and a long component from the triplet state  $^3\Sigma_u^+$  with 1.6  $\mu\text{s}$  decay time [2]. The quenching affects mainly the long component. Fitting an averaged pulse we measured the triplet decay time which was found to be only 800 ns. The ratio

of the intensities from the singlet and triplet state is 0.3 according to [2]. The measured triplet life time implies that only 60% of the maximum scintillation light is produced. Our estimate is therefore reduced to about 250 p.e/MeV. Minor reductions in the light yield are expected from the imperfection of the TPB coating, additional absorbers in the dewar etc.

If the reduced light yield from the triplet state is taken into account our theoretical estimate is rather close to the measured light yield.

### 2.5. *Anti-Compton veto*

Despite the limited energy resolution our system could still perform reasonably well as an anti-Compton veto for a HPGe detector. To test it we inserted an HPGe detector inside the coil of the WLS fibers. The HPGe detector was a p-type six fold segmented detector made by DSG Detector Systems GmbH. Because the crystal was damaged in the past it had a leakage current of about 6 nA. The best resolution achieved was 15 keV FWHM at 1332.5 keV on the core channel.

The DAQ was triggered on the HPGe detector. Pulse shapes of the HPGe detector for the core channel and all segments plus the pulse shapes of the twelve SiPMs were recorded simultaneously. As in the previous experiment we recorded 6  $\mu$ s long pulse shapes for each channel. Data was taken mainly with an external  $^{228}\text{Th}$  source.

The anti-Compton veto was applied off-line. From the recorded spectrum we produced a second spectrum by removing all the events when at least one SiPM registered a hit within a coincidence window of 6  $\mu$ s with the HPGe signal. Figure 10 shows the  $^{228}\text{Th}$  spectrum recorded with the germanium detector and the suppressed spectrum. In the Region of Interest (ROI) of the GERDA experiment ( $2039 \text{ keV} \pm 50 \text{ keV}$ ) the flat (Compton) background was suppressed by a factor 4.2.

It is even more convincing when we look at the Double Escape Peak (DEP) of the 2.6 MeV line (Fig.11). After a pair production by a  $\gamma$  the positron annihilates at rest and the two 511 keV  $\gamma$ s escape the HPGe detector. The energy deposited in the HPGe detector is the initial  $\gamma$  energy minus 1022 keV. The two 511 keV  $\gamma$ s will deposit all their energy within a short distance in LAr. The net effect is that we have 1 MeV converted in scintillation light in the same time when 1592 keV energy is deposited in the HPGe detector. These events should be vetoed with high probability. On the other hand a fully absorbed  $\gamma$  should not be vetoed.

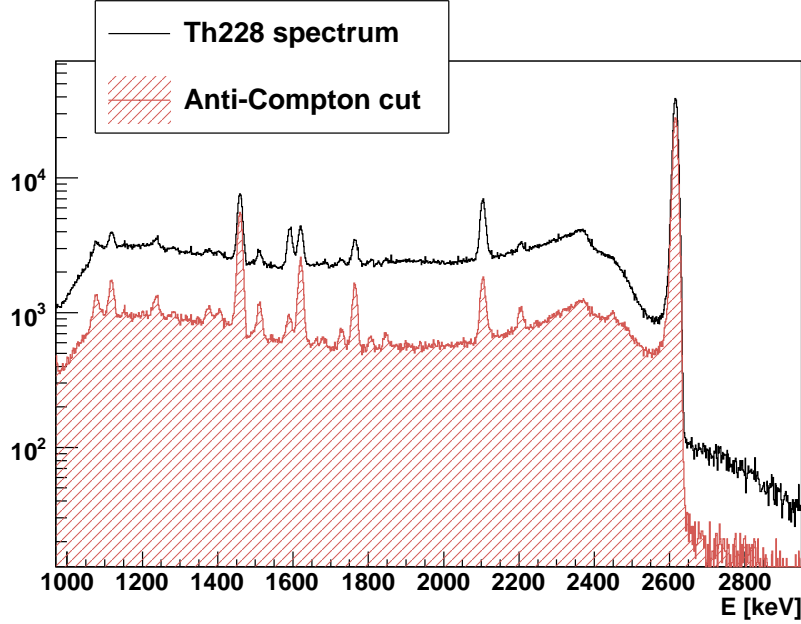


Figure 10:  $^{228}\text{Th}$  spectrum recorded with the HPGe detector. The red histogram is the same spectrum after the anti-Compton cut is applied with 0.8 p.e. threshold

As we can see in Fig.11 while the DEP peak is suppressed by a factor 6.1 the neighboring gamma line is only suppressed by a factor 1.1 with 0.8 p.e. threshold. The strong suppression of the DEP proves that the reduction of the Compton background is not due to a random coincidence.

### 2.6. Bias Voltage dependence

For practical use in a veto system the cross talk and afterpulse probability of the SiPM are much less important than the Photon Detection Efficiency. It is known that the PDE of the MPPC increases with the over voltage [6],[14]. To be sure that we operated our MPPCs at the highest possible efficiency we recorded data with three different voltages. In Fig.12 we see the same  $^{228}\text{Th}$  spectrum at increasing bias voltages. Fig.12 suggest that the number of p.e.'s increased significantly. On the other hand the veto efficiency did not increase too much. Fig.13 shows the suppression factors for the DEP and the Compton background around 2 MeV. Although we started our measurements at a very high over-voltage (2.5 V) the suppression factor (SF) for the DEP is still increasing until 2.8 V. From 2.8 V to 3.1 V the increase is negligible.

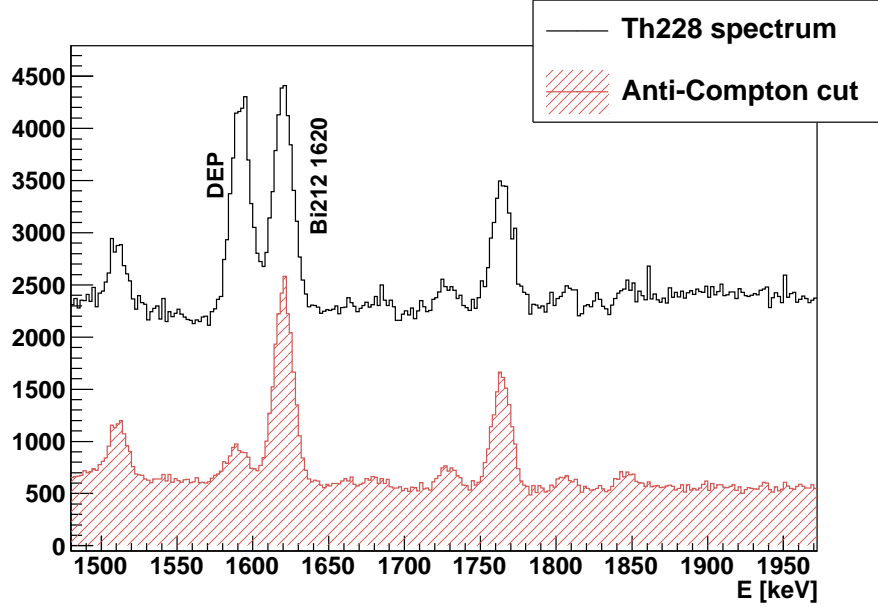


Figure 11: Suppressed spectrum of  $^{228}\text{Th}$ . One can see that the DEP is suppressed more than the neighboring gamma lines.

We can conclude that the increase in the numbers of pixels fired seen in Fig.12 is mostly due to increased cross talk and afterpulse probability and not real p.e.'s. Since a further increase of the veto efficiency was not possible we are sure that the maximal PDE was achieved. For the analysis in the previous section we used the data recorded at 2.8 V over-voltage.

### 3. Conclusion

We have demonstrated that the combination of SiPMs with wavelength shifting fibers is a viable alternative of large area PMTs for the detection of light in liquid scintillator experiments.

We also showed that the MPPC made by Hamamatsu can be operated directly submerged in the cryoliquid without major problems. The devices survived many cooling cycles without deterioration of their performance. It is worthwhile to note that when the SiPM is operated at such a low temperature the dark rate is negligible.

The setup described in this paper was built with regard to the needs of double beta decay and dark matter experiments. We expect that the

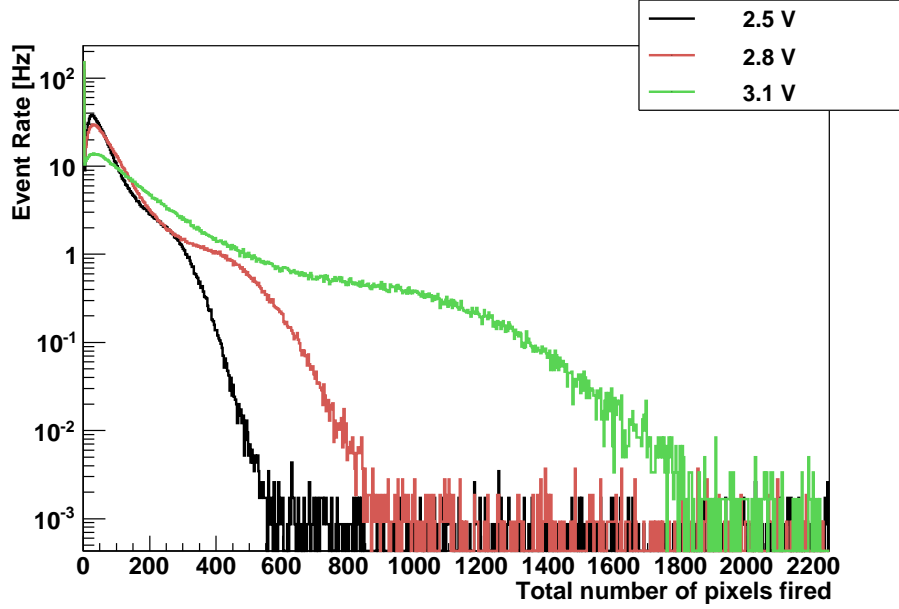


Figure 12: Spectrum of  $^{228}\text{Th}$  recorded with different over-voltages, without the HPGe detector

radioactive background induced by our solution is much smaller than by an equivalent setup with PMTs. The weight of the WLS fibers used in this experiment was only about 16 g. The holders and optical couplers can be further optimized and built from low activity materials. The activity of the materials needed for such a setup is currently under evaluation.

The full potential of the anti-Compton veto based on SiPMs and WLS fibers is not reached yet. Our setup suffered from the quality of the argon and the quality of the TPB coating could have been improved as well. In Section 2.3 we showed that the effect of the attenuation in the fiber can be minimized by using many short fibers. Increasing the number of fibers while keeping the number of electronic channels low would be possible in combination with larger area SiPMs that are already on sale. With further optimization the limit imposed by the trapping efficiency of the fiber should be possible to achieve.

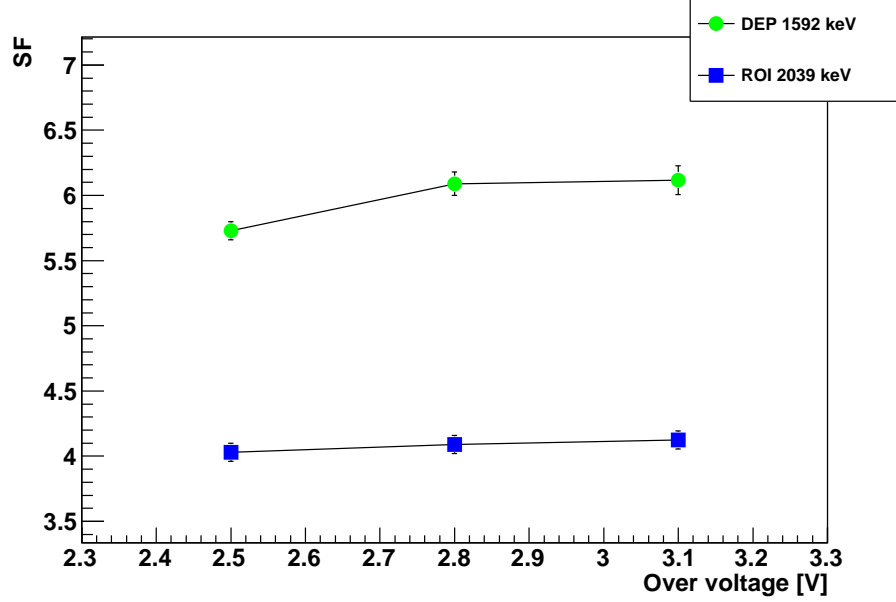


Figure 13: Suppression factors as function of over voltage

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